Short Baseline QVLBI Doppler Demonstrations-Part II

C. C. Chao and R. A. Preston
Tracking and Orbit Determination Section

H. E. Nance
DSN Systems Engineering

This report describes the continuation of the short baseline QVLBI demonstrations, which are designed to examine the stability of the current Doppler frequency system. A total of six passes of simultaneous two-way and three-way doppler data from Pioneer 10 were obtained at Deep Space Station (DSS) 11 and DSS 14. Results indicate that the short-term (min), medium-term (hr) and long-term (month) stabilities of the new rubidium frequency standard (HP 5065A) are 8 parts in 10^{13}, 1.3 parts in 10^{13}, and 1.9 parts in 10^{12}, respectively. The relative drift rate between the two systems (DSS 11 and DSS 14) is around 6 mHz/month. This indicates that the long-term stability of the current frequency system exceeds our limit level and makes the coming quasi very-long baseline interferometer (QVLBI) (MVM'73) demonstration very difficult.

I. Introduction

Accuracy analysis (Ref. 1) has shown that QVLBI data (differenced simultaneous two-way and three-way doppler) reduce navigation error produced by unmodeled spacecraft accelerations by 2 or 3 orders of magnitude. The inherent limitation of these data appears to be the frequency systems at the participating stations. In Ref. 2, it is shown that to account for spacecraft accelerations as small as 10^{-12} km/sec^2 (equivalent to about 5 m error in station location) requires frequency stabilities over one month of 2×10^{-14}.

This report describes the continuation of the short-baseline QVLBI demonstrations (Ref. 2), which are designed to examine the stability of the current doppler frequency system. The aim of this project is to determine whether the current frequency system using the new rubidium frequency standard (HP 5065A) is capable of supporting two-station tracking demonstrations (QVLBI). Results from Part I (Ref. 2) indicate that the long-term ($\approx 10^6$ sec) stability of the current system is on the order of 5 parts in 10^{12} ($\Delta f/f$). However, the measured value from Part I was based on only two passes of QVLBI data, and the second pass, which occurred 16 days after the previous one, had relatively poor data quality. Thus continued demonstrations as proposed in Part I were conducted.

A total of six passes of simultaneous two-way and three-way doppler data from Pioneer 10 were obtained at DSS 11 and DSS 14 from August 21, 1973, to September 23, 1973. By differencing these data types (QVLBI), we can study the stability of the entire local oscillator frequency chain at the DSSs, of which the station frequency standard is only a single component. A direct microwave link between the two stations was used as a less accurate means of monitoring the relative drift between the station frequency standards alone. During the same time period, two similar passes of doppler data from Pioneer 10 were obtained at DSSs 42 and 43. Because these two stations, which are about 200 m apart, use a common frequency standard, the QVLBI data will be free from the effects of frequency standard instabilities, and should provide us with an accurate method of examining the stability of the remainder of the frequency system for that station pair. This will help us to estimate the expected performance of the frequency system when a better frequency standard (cesium or hydrogen maser) is installed.

II. Data Acquisition and Processing

A summary of the data taken during the continuation of short baseline QVLBI demonstrations is shown in Table 1. The six passes of two-way and three-way doppler data obtained at DSSs 11 and 14 during a one month period have data arcs that vary from 2 to 6 hours. Since these six passes are rather evenly spaced over the month, we should be able to estimate the long-term stability of the frequency system. The two passes of data obtained from DSSs 42 and 43 are separated by a one-week interval and are 1.5 and 7 hours in length. All the doppler data were taken at S-band with a 60-second sampling rate.

To have a quick look at the results, pseudo residuals[1] were differenced by hand immediately after the completion of each pass. Such a procedure can be helpful in promptly locating problems in the performance of a demonstration, and affording an opportunity to correct the problems before the next scheduled pass of data.

For example:

(1) A 2-second difference between the time lags of the two-way and three-way data was found in the first pass of Doppler data at DSS 42 and 43. Unfortunately, efforts to correct this discrepancy were unsuccessful.

(2) A jump of approximately 80 mHz was noticed in the frequency bias for the fourth pass of data between DSSs 11 and 14. This was quickly attributed to an epoch error of 0.180 sec in the setting of the DSS 14 clock.

[1]Differences between real and predicted doppler data that are provided in real-time by DSN.

After all the data were obtained, the current orbit determination program (Ref. 3) was used to calculate the best theoretical estimates of the two-way and three-way doppler observables. The program Differ (Ref. 4) then produced the difference between the two-way and three-way residuals. During this demonstration the Sun-Earth-spacecraft angle was nearly 180 deg. Thus, the space plasma and ionospheric effects are at a minimum. This gives us confidence that the noise from charged-particle effects should be negligibly small when the two-way and the three-way data are differenced. The insensitivity of short baseline QVLBI data to uncertainties in tropospheric effects, baseline parameters and spacecraft position has been shown in Part I (Ref. 2). Hence, the differenced residuals should provide a good measure of the entire local oscillator frequency chain bias between the two stations. Observing the changes in this measured bias over a number of different passes of data allows the stability of the frequency system to be analyzed. A single pass of two-way and three-way doppler residuals and their differences is plotted in Fig. 1. It is interesting to note that the systematic rise in both sets of original residuals due to transmission media modeling errors at low elevation angles vanishes when the residuals are differenced.

III. Results and Discussion

As in Part I, we will discuss the short-term (minutes), medium-term (hours) and long-term (days and months) stabilities separately:

A. Short-Term Stability

Since the doppler data were sampled at one-minute intervals, the standard deviations of the QVLBI data residuals should give us a reasonable estimate for the short-term stability of the frequency system. Figure 2 shows the QVLBI doppler residuals for a number of the passes of data taken at DSSs 11 and 14. The values of the standard deviations of the residuals for each pass can be found in Table 1. The average value of the standard deviations, including the two passes from Part I, is 2.5 mHz. This corresponds to a stability of $\Delta f/f = 1.1 \times 10^{-12}$ for the entire two-station tracking system. Assuming the same performance at both stations, the contribution from each station is

$$\Delta f/f = \frac{1.1 \times 10^{-2}}{\sqrt{2}} = 7.8 \times 10^{-13}$$

Based on the two passes of QVLBI residuals (Fig. 3) from the Australian baseline (DSSs 42/43), we can estimate the stability of the system excluding the effects of the frequency standard. The average standard deviation of the QVLBI residuals using the DSSs 42–43 data is 1.11 mHz[2] or $\Delta f/f = 4.8 \times 10^{-13}$. The corresponding value for one station is

$$\Delta f/f = \frac{4.8 \times 10^{-13}}{\sqrt{2}} = 3.4 \times 10^{-13}$$

If the noise from rubidium standards is uncorrelated with that from other parts of the system, the estimated short-term stability for the new rubidium standard (HP 5065A) will be

$$\Delta f/f = \sqrt{7.8^2 - 3.4^2} \times 10^{-13} = 7 \times 10^{-13}$$

This value is in good agreement with the HP 5065A manufacturer's specifications (Fig. 4).

B. Medium-Term Stability

The medium-term stability (hours) may be estimated from the values of the slopes of straight lines that were fit through each pass (2 to 6 hours) of QVLBI residuals. The rms value of those computed slopes including the two passes from Part I is about 0.33 mHz/hr (Table 1). The rms slope of the residuals from the Australia baseline is 0.041 mHz/hr. The equivalent $\Delta f/f$ values are displayed in Table 2.

The observed medium-term stability for the rubidium standard is almost one order of magnitude smaller than the short-term stability. It is interesting to note that this medium-term value essentially agrees with the value obtained from a previous short baseline (DSSs 12 and 14) VLBI demonstration (Ref. 5), but is smaller than the HP 5056A manufacturer's specification.[3]

C. Long-Term Stability

The long-term (month) stability attracts most of our interest because, as shown from computer simulation studies (Ref. 2), it can seriously affect the accuracy of trajectories determined by QVLBI data. Figure 5 shows the pass-to-pass variation of the frequency biases obtained from QVLBI residuals on the Goldstone baseline. It is seen that a 6.0 ± 0.2 mHz change was found during the one month period. This is indicative of the long-term stability of the entire frequency system. Using the data from the Australian baseline, the long-term (8 days) contribution due to frequency system components other than the frequency standard was found to be 1.0 ± 0.4 mHz. The corresponding long-term $\Delta f/f$ stabilities are shown in Table 2. It should be remembered that these stabilities have been determined from only a limited amount of data, and hence, should be considered only order-of-magnitude estimates.

A comparison of the microwave measurements of the rubidium standard frequency bias on the Goldstone baseline and the QVLBI measurements of the corresponding local oscillator frequency chain bias is also shown in Fig. 5. The good agreement of these measurements indicates that the majority of the observed local oscillator frequency bias is indeed caused by a bias between the rubidium standards. The estimated uncertainty of microwave measurements is slightly less than 1 part in 10^{12} for a 4-hr integration time, which amounts to $1 \sim 2$ mHz uncertainty at S-band. Thus, we see from Fig. 5 that more than 90% of the bias is due to the new rubidium standards. This agrees with the medium- and long-term results from the DSS 42-43 baseline (Table 2).

D. Capability of Supporting QVLBI Demonstrations

As discussed in Part I, the desired level of long-term frequency stability was set at $\Delta f/f = 2 \times 10^{-14}$. This will allow the elimination of the error produced by 10^{-12} km/s^2 accelerations (Mariner-type spacecraft are typically subject to these levels). The observed stability of the current tracking system is about two orders of magnitude worse than the desired level. If the variation in the frequency bias may be simply modeled (e.g., linear ramp) over a few weeks time period, the stability requirements might be eased somewhat by allowing the bias model to be incorporated into the orbit determination program. The QVLBI determinations of frequency bias on the Goldstone baseline did seem to exhibit a linear drift (neglecting data prior to power failure on August 26), but the data length is not long enough (only one month) to draw definite conclusions.

IV. Concluding Remarks

The short-baseline QVLBI demonstrations provide us with a better understanding of the stability of the current tracking system. The results are summarized below:

(1) Short-term (min) stability is 8 parts in 10^{13}

(2) Medium-term stability (hr) is 1.3 parts in 10^{13}

(3) Long-term stability (month) is 1.9 parts in 10^{12}

---

[2]The 1.11-mHz noise may be partly due to the 2-sec difference between the time tags of the two-way and three-way data.

[3]The values of $\Delta f/f$ in this report have not been computed exactly according to the definition of an Allan variance, the most common means of judging the stability of a frequency standard.

The medium- and long-term values are approximate estimates due to limited samples. Additionally, it was found that more than 90% of the relative frequency bias between two DSSs was due to the frequency standards (HP 5065A).

The long-term stability of the current tracking system exceeds the desired as well as acceptable level of stability of high-precision QVLBI demonstrations. With the current system, the success of the present QVLBI demonstrations (MVM'73) becomes uncertain for spacecraft acceleration levels lower than 10^{-10} or 10^{-11} km/s^2. It appears that better frequency standards, like hydrogen masers, are highly desirable for QVLBI demonstrations. The nature of the long-term drifts of current rubidium standards should continue to be examined. This would increase the accuracy of the bias model in the orbit determination program, and also allow a better evaluation of how frequency uncertainties affect orbit determination.

Acknowledgment

The authors wish to thank Don Chaney, who scheduled the two-way tracking discussed herein, and other DSN and Pioneer mission personnel who helped in these demonstrations.

References

1. Ondrasik, V. J., and Rourke, K. H., "Applications of QUASI-VLBI Tracking DATA Types to the Zero Declination and Process Noise Problems," AAS 71-399.
2. Chao, C. C., et al., "Short Baseline QVLBI Demonstrations—Part I," JPL TR 32-1526, Vol. XVIII.
3. Moyer, T. D., "Mathematical Formulation of the Double Precision Orbit Determination Program," Technical Report 32-1527, Jet Propulsion Laboratory, Pasadena, Calif., May 15, 1971.
4. Johnson, D. E., "User's Guide to Differenced Partial Program," TM 391-333, June 9, 1972 (JPL internal document).
5. Thomas, J. B., private communication.

Table 1. Experimental summary: measured frequency biases and bias rates for individual passes of QVLBI data

	Date	Bias a,* mHz	Bias rate b,* mHz/hr	Standard deviation of QVLBI (σ) data, mHz	No. of data points
Goldstone Baseline DSS 11 & DSS 14 ($F3_{11}$-$F2_{14}$)	8/21	−34.86 ±0.14	−0.258 ±0.081	2.65	326
	8/22	−34.98 ±0.17	−0.196 ±0.246	2.08	137
	8/30	−29.93 ±0.20	0.021 ±0.024	2.51	147
	9/7	−31.73 ±0.34	−2.920 ±0.60	3.34	96
	9/13	−33.94 ±0.30	0.841 ±0.70	2.28	59
	9/23	−36.04 ±0.13	−0.316 ±0.10	2.03	225
	RMS		0.330	2.49	990 (Total)
Australia Baseline DSS 42 & DSS 43 ($F3_{42}$-$F2_{43}$)	8/30	−0.158 ±0.21	−0.108 ±0.43	1.66	65
	9/7	+1.342 ±0.07	+0.010 ±0.023	1.00	406
	RMS		0.041	1.11	471 (Total)

*Fit to a straight line $a + b(t - t_m)$, t_m time of mid-point of each pass

$$\frac{\Delta f}{f} = \frac{2.49 \times 10^{-3}}{2.3 \times 10^{9}} = 1.1 \times 10^{-12} \quad \text{short term}$$

$$\frac{\Delta f}{f} = \frac{0.33 \times 10^{-3}}{2.3 \times 10^{9}} = 1.5 \times 10^{-13} \quad \text{median term}$$

$$\frac{\Delta f}{f} = \frac{6 \times 10^{-3}}{2.3 \times 10^{9}} = 2.6 \times 10^{-12} \quad \text{long term}$$

Table 2. Measured frequency stabilities

	No. of Stations	Short term (min)	Medium term (hr)	Long term (days ~ month)
Entire tracking system	Two[a]	1.1×10^{-12}	1.54×10^{-13}	2.6×10^{-12}
	One[a]	7.8×10^{-13}	1.10×10^{-13}	1.85×10^{-12}
System excluding standards HP5065A	Two	4.8×10^{-13}	1.8×10^{-14}	4.4×10^{-14}
	One	3.4×10^{-13}	1.3×10^{-14}	3.1×10^{-14}
Frequency standards HP5065A	Two	7.8×10^{-13}	1.50×10^{-13}	2.6×10^{-12}
	One	7.0×10^{-13}	1.10×10^{-13}	1.85×10^{-12}

[a]One-station system $= \dfrac{\text{two-station system}}{\sqrt{2}}$

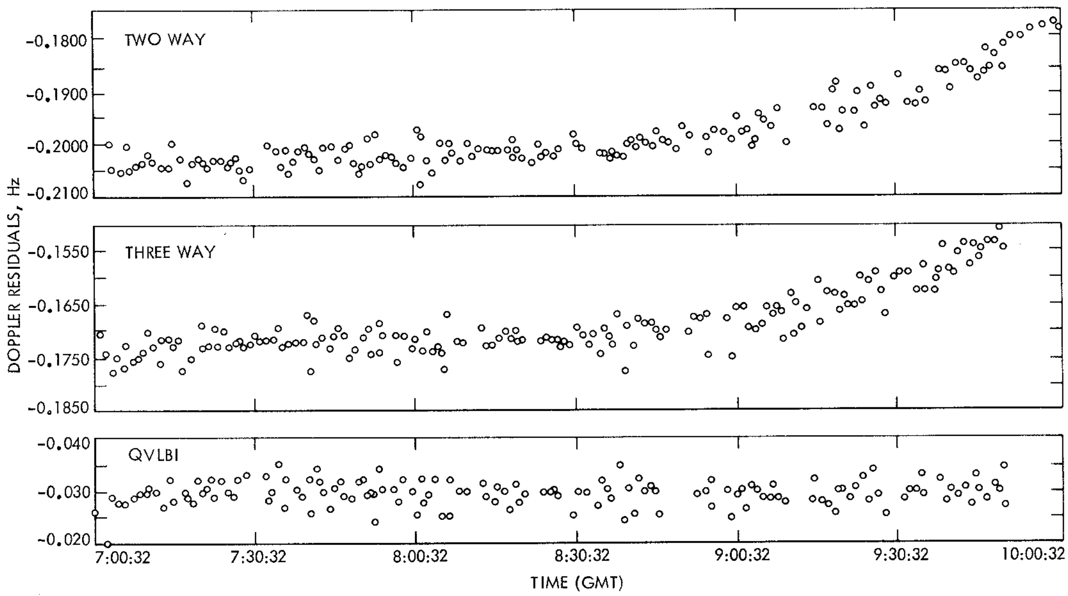

Fig. 1. Two-way, three-way, and QVLBI doppler residuals on Aug. 30, 1973, at DSS 11/41

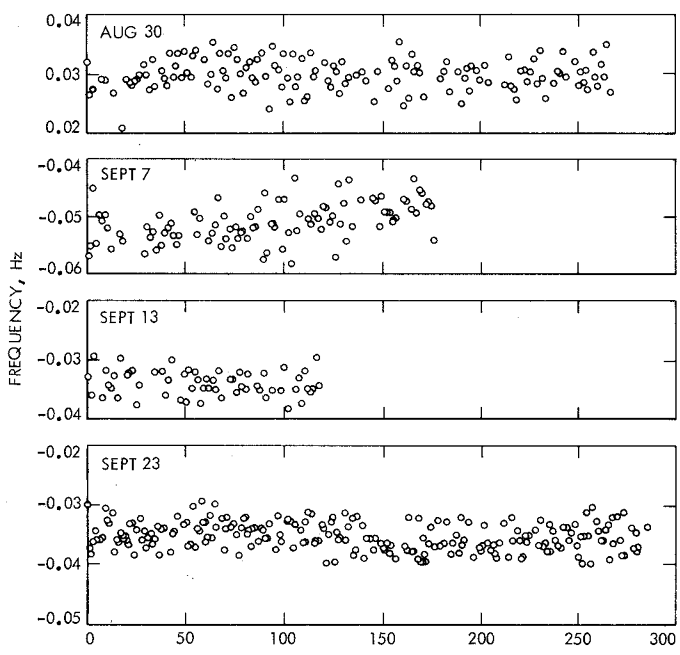

Fig. 2. QVLBI doppler residuals for a number of passes on the DSS 11/14 baseline

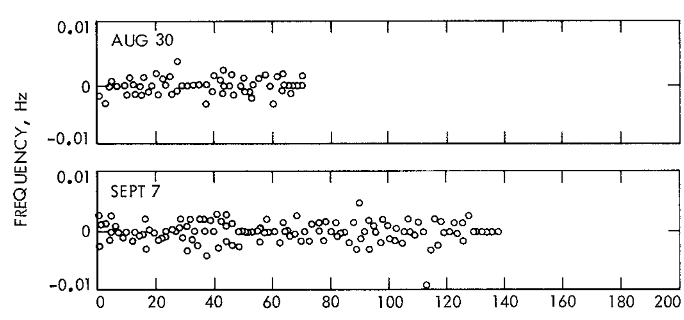

Fig. 3. QVLBI doppler residuals on the DSS 42/43 baseline

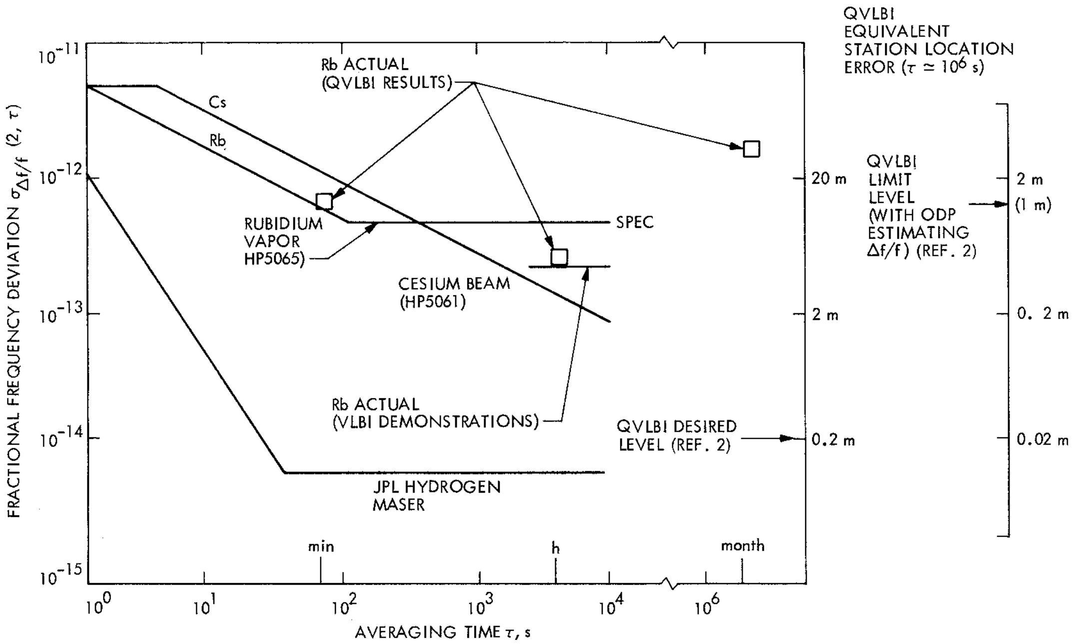

Fig. 4. Comparison of short-baseline QVLBI demonstration results with specifications of various frequency standards and requirements of the QVLBI data type

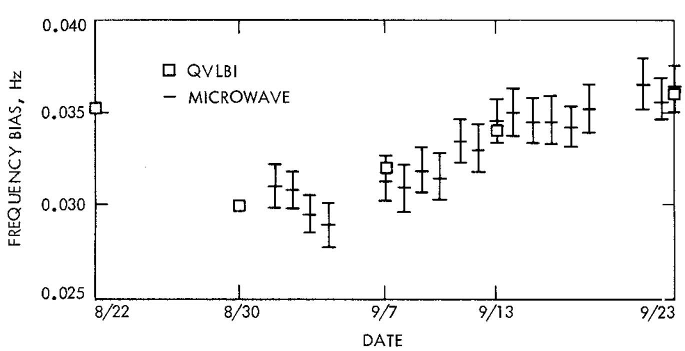

Fig. 5. Comparison of QVLBI determinations of system frequency bias (DSS 11/14) and microwave determinations of frequency standard bias